DEVELOPMENT OF NANO-COMPOSITES FOR ELECTROMAGNETIC INTERFERENCE (EMI) SHIELDING APPLICATION

A SYNOPSIS

Submitted by

AVINAH SUDAM SHINDE

(Reg. No. 201814295)

in partial fulfillment for the award of the degree

of

DOCTOR OF PHILOSOPHY

DEPARTMENT OF MECHANICAL ENGINEERING
SCHOOL OF MECHANICAL, AERO, AUTO AND CIVIL ENGINEERING
KALASALINGAM ACADEMY OF RESEARCH AND EDUCATION
(DEEMED TO BE UNIVERSITY)
ANAND NAGAR, KRISHNANKOIL – 626 126
TAMIL NADU, INDIA
AUGUST 2022

1. INTRODUCTION

The massive growth in use of electronic devices like, mobiles, computers, laptops and the satellite communication in numerous industries, including defence, aerospace, automobile, and even everyday life has increased the worry about the electromagnetic (EM) radiation exposure. Without computers, cell phones, Wi-Fi, and other electronic gadgets, it is inconceivable that online education and the work-from-home culture would have exploded in the post-covid era. The increasing use of all electronic devices has spawned a different sort of pollution which is termed as electromagnetic interference (EMI).Electromagnetic interference (EMI) occurs when erroneous or unintentional EM signals sent by an electronic equipment interfere with and degrade the operation of other electronic devices as well as it hampers the functioning of biological systems. Prolonged exposure to electromagnetic waves germs human health hazards like sleeplessness, anxiety, fatigue etc. The study carried out in Europe reveals that approximately 1.5-2 % rise in the childhood leukaemia due to extremely low frequency magnetic fields [1]. Medical implants used in the human body are also susceptible to these EMI waves. However, our dependency on technology has reached to such a level that abandoning them would be a "crazy fantasy." Rather soon we would witness an exponential rise in the use wireless communication devices.

However, nobody is talking about this invisible environmental pollution and rather we are working only on the visible environmental pollution. We even do not botherthat this kind of pollution really exists, and it is as harmful as visible pollution. EMI Shielding can really help to reduce this pollution and protect the devices from EMI. EMI shielding is done by a suitable shield material which will either reflect or absorb the EM waves. There is good demand from the aerospace industry and military for EMI shielding material as it is very crucial that each device performs in the environment of tremendous EM pollution.

The EMI shielding material must have qualities such as strong conductivity, light weight, and good manufacturability, without sacrificing mechanical performance. By increasing conductivity with appropriate filler, EMI shielding performance may be significantly enhanced [2]. Metals are being used traditionally for EMI shielding, but they have an inherent limitation of heavy weight, susceptible to corrosion and cost [3].The metals with porous matrix is found to be having more EMI shielding effectiveness (SE) however, it also reduces the mechanical performance of the

composite [4]. Polymers can be best candidates to overcome these limitations of metals. Also their thermal, mechanical, electric properties can be greatly tailored by addition of different fillers [5].Thenumber of fillers, including metals, carbon black, graphite, ferrite, graphene, is added to polymer matrix to improve their EMI SE. Among the different elastomers silicon rubber is extensively used in electronic, medical and aerospace applications due to its exceptional thermal stability [6] and weather resistance [7]. Improvement in properties like conductivity [8], thermal stability [9], mechanical properties has broadened the use of silicon rubber and makes it suitable for EMI shielding also.

With the rapid growth in the EM pollution there is urgent demand for EMI shielding material.The primary objective of this research is to develop a nanocomposite for EMI shielding application.

2. LITERATURE SURVEY

There are basically three different mechanisms of EMI shielding viz. reflection (R), absorption (A), and multiple reflections (M). Shielding effectiveness is the measure of total energy due to all the components viz. reflection, absorption and multiple reflections which is measured in dB. The factors which influence the shielding effectiveness of the material are listed below.

- Conductivity
- Permittivity, permeability
- Thickness
- Frequency of the EM wave
- Type and distance of source

There are numerous materials used for EMI shielding viz. metals, composites of metals, conducting polymers, polymer composites, silicon rubber etc. Metals are good candidates for EMI shielding due to their high electrical conductivity. However, their weight is limiting their use to high strength application only. Conducting polymers are another suitable option but compared to reinforced polymer they possess less strength. Therefore developing a lightweight material with good EMI shielding as well as strength is still in demand. The typical EMI shielding material should possess some important characteristics as listedbelow.

- Strong absorption in broad spectrum
- Good mechanical and thermal properties

- Corrosion resistant with long life
- Light weight
- Easy to process and cheap

Compared to all the metals, aluminium being light weight, good mechanical strength and high conductivity,is the favourite metal for EMI shielding. For low cost applications steel can replace aluminium. It works well for low frequency shielding in KHz range. Aluminium and its alloys have very high electrical conductivity which is the major criteria for EMI shielding application. The reflection component of Al alloy is more as compared to the absorbed component of incident EM waves. The absorbed component can be improved by adding the different fly ash particles [10]. The oxidation and galvanic corrosion of Al limits its applications. Addition of small amount copper in epoxy matrix improves the EMI SE considerably [11]. Copper alloy 770 which is combination Ni and Zn is mostly preferred due to its good corrosion resistance. High cost limits its use for different applications. Magnesium and its alloys may be very useful for EMI shielding because of its less weight compared to steel and aluminium. Apart from the weight, metals have another limitation that, metal used as EMI enclosure for devices tends to leak at joints. To alleviate this problem a flexible or high resilient material, which is also effective for EMI shielding, is needed.

The polymers are non-corrosive, flexible and easily moldable and hence they can comfortably replace the metals. The current demand and the miniaturization of the electronic devices can be fulfilled by the lightweight advanced polymers. Currently two major category of polymers are being used viz. intrinsic conducting polymer (ICP) and conductive polymer composite (CPC) which has desirable electrical conductivity, are light weight, with good chemical and corrosion resistance [12]. Majority of polymers are basically non-conducting in nature. Insulating polymers like polystyrene, poly (PVDF), polypropylene (PP), poly methyl methacrylate (PMMA) poly vinyl alcohol (PVA), polyethylene (PE), poly vinyl pyrrolidone, epoxy etc. are getting increased attention because of their low weight, corrosion resistance, chemical resistance and good thermal operating range [13]. The main hurdle in using them is their insulating nature which can be comfortably overcome by adding different conductive filler into them. These conducting polymer composites (CPC) are manufactured with variety of fillers of different shapes, size and proportions [14]. Amongst all conductive fillers, carbon black (CB) Antunes and Velasco, [15], carbon fibers (CF)[16]and the nano-fillers like MWCNT [17], graphene flakes [18] are

explored extensively due to high aspect ratio, high conductivity and easy manufacturability. These polymer materials are proposed and explored by the researchers for varied applications and frequency range. They found these polymer materials attractive and suitable for EMI shielding applications.

Carbon based nanoparticles lately being used in the electronic industry due to their good mechanical and electrical properties. Even at very low weight percentage of these fillers they exhibit outstanding properties which are useful for different applications like electrostatic discharge, electrostatic painting, EMI shielding etc. [19]. CNT and graphene being low density nanoparticles are promising candidates for the reinforcing the polymers to form an advanced nanocomposite. Variety of polymer matrices used with CNT for exploring their EMI shielding characteristicsand it can be observed that majority of studies are carried out in the x band frequency range.

Compared to other polymeric materials silicon rubber elastomer (SR) is having better thermal stability, chemical resistance, flexibility and weather resistance [20]. Because of these advantages SR is used in varied fields such as automobile, aerospace, medical etc. Improvement in properties like conductivity, thermal stability, mechanical properties has broadened the use of silicon rubber.By improving the electrical conductivity of SR it can be used for EMI shielding applications also [21].

Due to viscoelastic nature of rubber the properties keep changing with respect to time. That's why the mechanical and tribological performance of these materials depends on the molecular structure. Estimation of tribological performance becomes difficult due to this complex structure [22]. Graphene gives a good solution for friction control in various applications [23]. The thermal mechanical and electrical properties of graphene are superior to conventional materials.

3. RESEARCH PROBLEM

This research is motivated by the increasing demand for EMI shielding to produce a material that is flexible, simple to manufacture, and cost-effective. In automotive and aerospace applications, the leakage of EM waves via the joint is also a significant issue. To counteract this, flexible EMI shielding material that can prevent this leakage is required.

For the majority of conventional EMI shielding materials, reflection is the primary shielding method. Therefore, these shields safeguard just the gadgets covered by these materials. However, because the EM waves are reflected by the shield, they

tend to interfere with other electronic devices. Therefore, materials with absorption as their primary shielding mechanism are required.

In addition, all past research has concentrated on enhancing the EMI SE of materials. Very little thought is given to the adaptability of the composite production process. Therefore, there is a need for research into EMI-shielding materials that can be manufactured using normal techniques and are cheap for any use, including aerospace, military, and even consumer items. In addition, a significant obstacle addressed by the research community is the uniform dispersion of fillers inside the polymer matrix.

This research seeks to answer the aforementioned questions and provide a sustainable manufacturing solution by employing the melt blending manufacturing technology. Roll mixing and compression moulding, two of the most common machines utilised in the production of rubber products, are used to manufacture the samples in this study. This study's realism and commercial viability are enhanced by the use of a conventional method for producing rubber. In this study, we created silicon rubber nanocomposite with a variety of nano-fillers that we feel could solve the aforementioned problems.

4. OBJECTIVES OF THE THESIS

The research plan is shown in Figure 1. The important objects of this work are:

1. To assess the machinability of sandwich structures which can be used as an EMI shield
2. To choose appropriate Nano-fillers and polymer resin in order to create a novel nanocomposite.
3. Mechanical, tribological, and thermal characterization of created Nanocomposites are to be performed.
4. To investigate the conductivity and dielectric characteristics of nanocomposite
5. To examine the EMI Shielding Effectiveness (SE) of nanocomposite.

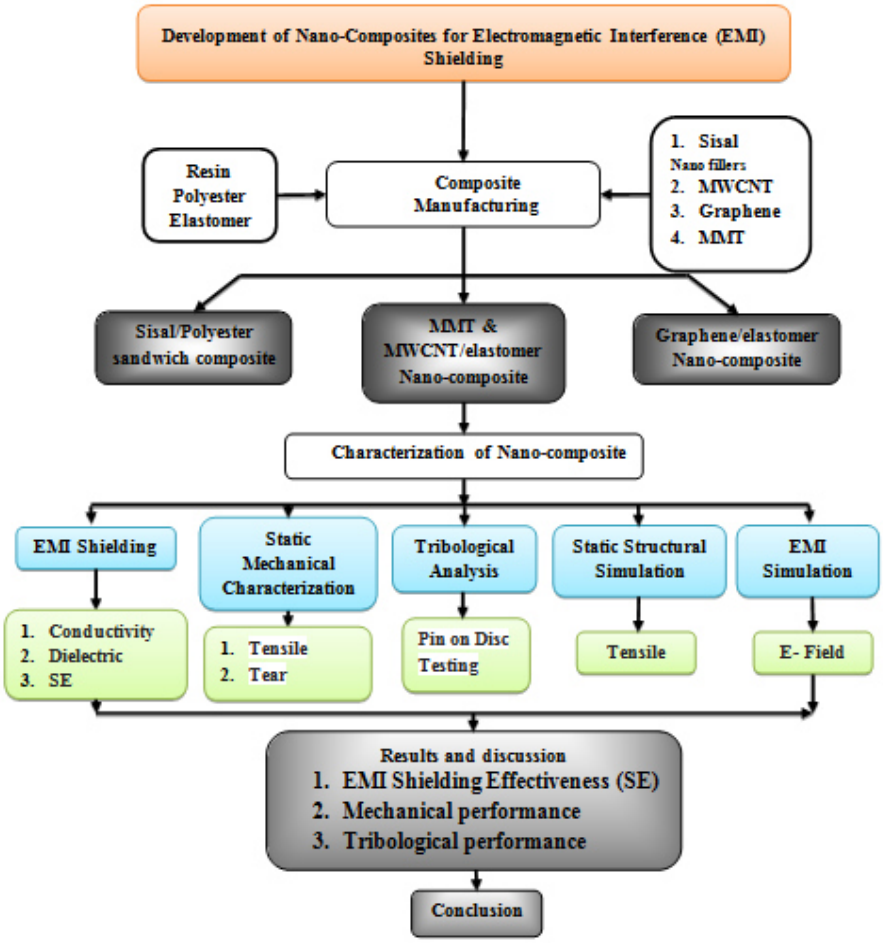

Figure 1 Research plan

5. MATRIALS AND METHODS

The primary objective of development of nanocomposite for EMI shielding application with different composite blends is studied for the frequency range of 1 MHz to 1 GHz. Weight percentages of fillers is varied for tuning the required EMI SE. The conductivity and dielectrics properties are also evaluated as the literature mentions it's important in the study of EMI.

Compared to other polymeric materials silicon rubber elastomer (SR) is having better thermal stability, chemical resistance, flexibilityand weather resistance. Because of these advantages SR is used in varied fields such as automobile, aerospace, medical etc. It is used in aerospace for different parts like some space suit elements, automobile gaskets, seals, sealants, food molds, medical equipment such as seals, tubes, valves etc. Due to these numerous advantages silicon rubber of SH5060 grade is selected for manufacturing the EMI shielding material. The selected grade of

silicone SH5060 is able to withstand the temperature as high as 454 ℃. Peroxide based curing agent DICUP40 is used for initiating the polymerization reaction.The shelf life of the peroxide cured silicon rubber is almost one year which reduces the wastage of materials also.

5.1. Selection of material

Three different fillers are tried namely MMT, MWCNT and graphene. The literature enlists the study of different polymer materials with CNT and graphene and their usefulness for EMI shielding applications. Considering all these aspects the filler materials are selected. SR with SH5060U grade and peroxide-based curing agent such as Dicumyl Peroxide (DCP) of 40 % purity were compounded with different weight concentrations of nano clay viz. 0, 0.5, 2, 5 % and are hereafter referred to as SR1, SR2, SR3, and SR4. The mixing was carried out for about 40 minutes on a two-roll mill machine. The compound was cured in a SANTEC make compression molding machine of 30 Ton capacity. The temperature, pressure, and curing time maintained are 170℃, 50 bar and 5 min, respectively; followed by the post-curing at 200℃for 4 hr. in a hot air oven (Make: Athena Technology, Model: ATAO - 3 S/G). Required specimens as per ASTM standard are cut from the prepared sample plates for tensile and tribological testing. The nomenclature used for different compositions of MWCNT is SRC1, SRC2, SRC3, SRC4, and SRC5 for 0, 1, 3, 5, and 7 % of MWCNT respectively. Similar nomenclature used for different compositions of graphene is SRG1, SRG2, SRG3, SRG4, and SRG5 respectively.In manufacturing the sandwich composite PVC core withpolyestermatrixis used. Three different combinations of PVC, sisal and glass viz. Glass/PVC/Glass, Sisal/PVC/Sisal and Glass/PVC/Sisalare manufactured. First machining trials are performed on thesesandwich composite as ultimately the skins manufactured by nanocomposite can be used for manufacturing the sandwich composites.

5.2. Characterization of nanocomposite

5.2.1. Morphological characterization

The field emission scanning electron microscopy (FE-SEM) is used to obtain the secondary electron images of fractured surfaces after the tensile testing as well as the worn surface morphology after the tribology testing. The crystallinity of different samples is determined using the XRD analysis. XRD was carried out to analyze the maturity and formation of the nanocomposite. FTIR analysis is used for identifying

the organic, polymeric or inorganic materials from the sample. This can be used for chemical identification.

5.2.2. Abrasive machining of sandwich composite

The experimental work is performed on the CNC DARDI AWJ machine. The available pressure range was from 60 to 400 bar. The nozzle diameter of 0.7 mm with impacting angle of 90° is kept same for all experiments. An abrasive garnet with 80 mesh size is used. The length of the cut is 20 mm. The AWJM controlling parameters are standoff distance (SOD), water jet pressure (JP), and traverse rate (TR). Based on the literature and available AWJ machine working range, parameters level is decided.

5.2.3. Mechanical characterization

A sample preparation and testing for tensile and tear test is performed according to ASTM D412 and ASTM D624, respectively. The tensile test is performed at a speed of 450 mm/minwith an environmental condition of 24°C and 54 % humidity. Shore hardness testing is done according to ASTM D2240.

5.2.4. Experimental Design of Tribological Study

Taguchi's L_{16} orthogonal array is used with different levels of control parameters to design of tribological experiments. Pin on disc wear testing machine is used, and tests are performed according to the ASTM G99 standard. The samples are cut in the form of a rectangular pin of 10 × 10 × 30 mm. The rubbing disc is made of EN-31 of hardness 60 HRC.

5.2.5. Dielectric properties and EMI SE measurements

The permittivity, permeability and loss tangent for different samples are measured at room temperature in the frequency range of 1 MHz to 1 GHz using an LCR meter (model E4980 A precision impedance analyser, Agilent). EMI SE measurements of 1 mm thick samples are carried out by a waveguide transmission line method using vector network analyser (VNA) (Agilent Technologies E5071C, ENA series, 1MHz–1 GHz, CA). The samples are placed between the WR 510 waveguide connected through a coaxial cable to the VNA ports. The calibration of the waveguide is carried out before actual measurements. The scattering parameters S_{11} and S_{12} corresponding to thereflected and transmitted signals are measured and EMI SE is calculated. The relative permittivity is also calculated from the scattering (S) parameters from Nicolson, Ross and Wire algorithms using the inbuilt software.

6. RESULTS AND DISCUSSION

6.1. Abrasive machining performance of sandwich composite

Stand of distance (SOD) was the most significant parameter which affected the Kerf Taper (KT) angle. The least KT can be achieved with a smaller SOD during the machining of S-sandwich panels.Higher value of SOD results in more divergence of the jet, which reduces the jet intensity on the outer periphery**.** Also, as the jet penetrates through the work piece, its kinetic energy and momentum decrease further, resulting lesser kerf width at the bottom of sandwich panels. Smaller SOD produces minimum surface roughness. JP was determined as the next influencing parameter on surface roughness. The optimum value of SR was obtained at a lower level of pressure and a medium level of traverse rate. The surface roughness was the most excellent for JP from 190 to 230 MPa and TR of greater than 15 mm/min. Meanwhile, the surface roughness was minimum and independent to TR for the SOD of 1mm. The higher value of pressure results in higher kinetic energy to abrasive particles, which ultimately responsible for materials removal. This also decides the ability of jet to cut through-thickness with ease. Thus, with increased jet pressures, the traverse speed can also be increased to give higher MRR. The SOD was proved to be insignificant in deciding the MRR. The MRR value was the highest and independent of JP and SOD for TR of 30 mm/min. However, for better MRR value, JP and SOD should be maintained in the range of 200 to 230 MPa and 1.5 to 2.3 mm, respectively.

6.2. Mechanical characterization of composite

The existence of individual constituent peaks in the SR4, SRC5 and SRG5 composite confirms the correct formation of the respective composites.The tensile strength of the all the compositions i.e. SR-MMT, SR-MWCNT and SR-Graphene nanocomposite is found to increase with an increase in the weight fraction. The highest value of tensile strength is 6.02 MPa which is 11.68%higher than the SR1 composition. Pure silicon rubber exhibited tensile strength of 5.36 MPa, which improved to 14.74 MPa for SRC5 composition; it increased to 16.76 MPa for SRG4 composition. This is 173 %and 213 % higher than the pure Silicone rubber for SR-MWCNT and SR-Graphene composites.

The highest tear strength value is 12.36 MPa for the SR3 composition which is 6.55 % higher than for the pure SR. With increase in MWCNT concentration, the tearing strength goes on increasing and reaches maximum value of 3.57 MPa for

SRC5 composition.The ripping strength falls as the graphene concentration increases, reaching 5.41 MPa for SRG5 composition.

The highest shore D hardness of 52 is observed for SR4 composition. This increase is almost 16 % higher than the pure SR composition. The optimized amount of the MMT concentration in the SR is 2 % as compared with other configurations under study.The highest shore A hardness is 48 for SRC5 composition. Almost 33 % rise can be observed as compared with pure SR composition. After SRC3 composition, very marginal improvement from SRC4 to SRC5 is evident. The highest shore A hardness is 54 for SRG5 composition.

SEM images showenhanced filler content and uniform distribution are justifying increases in characteristics for all composition. SRC4 and SRC5 composition does show a very marginal improvement in the properties. This may be due to voids as observed in the SEM images. This also means the starting phase of agglomeration of MWCNT with increase concentration.A decrease in the characteristics of the SRG5 composition is noticed, which could be related to cracks produced due to vacancies in the SRG5, as seen in the SEM image.

6.3. Tribological characterization of composite

The experiments are designed according to Taguchi's L_{16} array. Different levels of load, sliding speed and sliding distance are selected. Influence of normal load and sliding velocity graphs are plotted against the composition. The SEM analysis of worn surface is done to understand the wear pattern.

At 10 N loading, the COF reduces by almost 25 %, from 0.950 to 0.710, for the SR3 composition compared with the SR1 composition. At the same time, a 60 % reduction of the wear rate is observed at 10 N loading for the SR3 composition as compared to the SR1 composition. The COF and wear rate are the highest for a load of 10 N. However, for 40 N loading, a dramatic behaviour is observed where the COF reduces, and the specific wear rate increases as against the trend due to an increase in the MMT concentration. When the applied load increases to 30N, a significant reduction in the COF by 52.11 % is observed in the SR3 composition. After 30 N the COF is found to increase by 20 % to 0.425. When the sliding velocity is lower, more surface-to-surface contact with the friction plate is experienced, resulting in an increasing COF and wear rate. The lubricant film formed between the contacting surfaces is due to the wearing down of polymeric material.

For SR-MWCNT composition the COF and SWR are found to be at their peak for a loading of 10 N, and they begin to decline as the load is raised. This is because lighter loads are not adequate to disrupt the interfacial bonding; lighter loads do not result in the formation of chips. At a constant loading, the COF and SWR tend to decrease as the nano filler concentration rises up to the point when the SRC3/SRG3 composition is reached, but then they sharply rise again for the SRC4 to SRC5 and SRG4 to SRG5 compositions. A trend analogous to this one can be seen when sliding at a constant speed. When the sliding speed is increased, the COF and SWR both go down. As it degrades, rubber has a predisposition toward the formation of a layer that acts as a lubricant. It should come as no surprise that the SRC3 composition achieves the best tribological performance when compared to the other compositions.

SEM analysis shows pure silicon rubber has poor mechanical strength. Hence, it is susceptible to adhesive friction. For the SR4, SRC2 and SRG2 composition, the nano particles are found to chip off. The particles getting chipped off from the surface form a lubricating film (transfer film) between the disc and specimen surface. The transfer film decreases the adhesive wear, as seen in the SR1 composition. For 5 wt. % of the MMT, localized material removal is seen in the SEM imaging. According to the SEM pictures, adhesive wear is the primary and most basic mechanism of wear.

6.4. Modeling and simulation of SR-MMT composition

For unit cell modeling the 3 tensile and 3 shear load cases are simulated by applying macroscopic strain in each direction and finding the reaction forces. These reaction forces are in turn used to evaluate the stiffness matrix.RVE is assumed to be of unit volume. Three different load cases are selected, viz. load X_{11}, load Y_{11} and Z_{11}. The u, v and ware the displacements along X, Y and Z directions, respectively. The average stresses and strains are calculated using the constitutive equations.The material designer module available in the Ansys is used for generating the RVE by setting the size and weight fraction of MMT. The elastoplastic material model is used to model the silicon rubber's deformation process. In this model the equivalent plastic strain at the damage is a function of the equivalent strain rate. Compared with the RVE model the H-T model predicts higher values of longitudinal modulus with 17.4 % as the highest deviation for 0.06 % of MMT. Shear modulus highest deviation from RVE results is 4.81 % for 0.2 % of MMT. For all other reported properties, the RVE model goes in line with the analytical models.

6.5. Dielectric and EMI SE study

The dielectric properties of the SR-MWCNT and SR-graphene is analysed using the VNA in the frequency range of 1 MHz to 1 GHz. The AC conductivity is found to improve with increase in the filler concentration for both the compositions. SRC5 and SRG5 compositions with 7 % filler loading are found to exhibit highest increase in the conductivity. SRC1 composition being a pure silicon rubber has conductivity near to zero while it increases to a highest value of around 0.013 S/cm for SRC5 composition and for SRG5 it goes to a highest value of around 2.98 X 10^{-3} S/cm at 1 GHz.A sharp rise in the conductivity is observed for SRG3 (3 wt. % graphene) composition is evident from theanalysis. This indicates the percolation threshold of SRG is 3 wt. % graphene. The formation of conductive network due to densely populated nano filler network leads to transfer of electrons between the particles due to tunnelling effect. Conductivity also increases due to high aspect ratio and effective dispersion of the filler.

From the analysis of conductivity and EMI SE with different compositions it can be seen that as conductivity increases the EMI SE also increases. The conductivity for pure silicon rubberis nearing to zero while EMI SE is 3.63 and 0.74 dB at 1 MHz and 1 GHz frequencies in that order. As the MWCNT loading increases EMI SE also increases and reaches to maximum value of 48.03and 52.18 dB for SRC5 composition and 32.94 dB and 43.22 dB at 1 MHz and 1 GHz respectively for SRG5 composition. This shows the influence of nano filler concentration on EMI SE which can be attributed to physical properties viz. surface area, aspect ratio and availability of more number of atoms at the surface. The availability of free electrons increases with increase in the weight percentage of filler which leads to improvement in the conductivity and in turn the SE.

For the materials to be used for shielding applications the mechanism of shielding is very important. Variation of total (SE_T), absorption (SE_A) and reflection (SE_R) SE with respect to change in frequency are analysed. The absorption and reflection SE both adds up to get the total SE (SE_T). As can be seen from the analysis the absorption component contributes more than the reflection component. For pure silicon rubber the SE_A and SE_R ranges between 1-3 dB and 0.2-0.5 dB respectively over the entire frequency range. The SE_A and SE_R value goes to as high as 52.16 and 7.82 dB respectively for SRC5 composition for the same frequency range. However, the SE_A and SE_R value goes to as high as 39.6 dB and 6.52 dB respectively for SRG5

composition for the same frequency range. The reason for higher SE_A component is multiple reflection from the conducting interfaces Sang et al., [24].

To authenticate and comprehend the EMI shielding mechanism of different compositions, HFSS model is created. This model simulation gives an insight into the EM wave propagation through different compositions.A WR510 waveguide for the frequency range of 1-3 GHz is modelled. Air is used as a medium inside the wave port. A wave port excitation available in the HFSS is applied to port 1 and 2 i.e., S_1andS_2. The experiments are inputted to the shielding plate. The simulation is run for the frequency step of 0.1 GHz.With MWCNT loading of 5wt. % i.e., for SRC4 composition the electric and magnetic field strength is drastically reduced. When the loading increase to 7 wt. % i.e., SRC5 composition, (~52 dB) and the electric and magnetic field almost disappeared. Similar behaviour is observed for the SR-graphene composition. It is interesting to note that all compositions are unresponsive to the magnetic field of EM waves, suggesting the minimal magnetic loss at the interface among the plate and EM waves. This points out that the attenuation happens because of conductive losses i.e., reflection and absorption, which is supporting the experimental observations.

7. CONCLUSION

This research has opened up new possibilities for the production of flexible EMI shielding material. Utilizing a commercially viable, scalable, and easily adaptable manufacturing approach, the silicon rubber-based nanocomposite is successfully fabricated. To synthesise the EMI shielding material, no new setup, sophisticated synthesis, or costly procedure is required. In the presence of a peroxide-based curing agent (DICUP40), the solid silicon rubber and nano fillers MMT, MWCNT, and graphene are combined in a two-roll mill machine. The material is then compression-molded into sample plates. In conventional rubber production, identical equipment is required to create rubber products. Therefore, the developed material may be utilised to manufacture a variety of items, such as rubber seals, gaskets, packaging products, etc., which can be used directly to protect various devices from EMI leakage.

SR/MWCNT nanocomposite is the first composite to be successfully made using compression moulding and tested for dielectric and EMI SE performance. The analyses of XRD and SEM confirm this. Within the frequency range of 1 MHz to 1 GHz, the inclusion of MWCNTs improves the dielectric and EMI SE performance, as

determined by an investigation. This is justified by the enhanced conductivity resulting from the use of MWCNT fillers. The SRC5 (7 wt. % MWCNT) composition demonstrates EMI SE values of 48 dB at 1 MHz frequency and 52.18 dB at 1 GHz frequency. It has been determined that the absorption mechanism dominates the overall EMI SE for the SR/MWCNT mixture. The HFSS simulation of EM waves validates and justifies the experimentally determined performance of the composite material.

SR/graphene nanocomposite is the second composite successfully produced. Additionally, similar investigations are conducted on this substance. Due to the presence of graphene, both dielectricity and conductivity are considerably enhanced. Graphene's percolation network results in outstanding dielectric characteristics. The percolation threshold of graphene has been determined to be 3 wt. % graphene (SRG3 composition). The SRG5 (7 wt. % graphene) composition demonstrates EMI SE values of 32.94 dB at 1 MHz frequency and 43.22 dB at 1 GHz frequency for a 1 mm thick sample. The enhanced SR-graphene interface contributes to the interfacial polarisation, while the material with a high dielectric constant generates electric dipoles, resulting in the absorption-dominated EMI shielding.

SR/MMT, SR/MWCNT, and SR/Graphene are evaluated for their mechanical and tribological performance, respectively. When investigated for mechanical and tribological performance, the MMT–SR nanocomposite revealed exceptional features that are suitable for diverse automotive and non-automotive applications. Besides, essential tribological characteristics like load, sliding speed, and sliding distance were examined using ANOVA. Also done were FESEM and EDS analyses of the broken and worn surfaces. Two percent SR/MMT nanocomposite had the greatest tensile and tear strength. Compared to SR1, the tensile and tear strength of the SR3 composition increased by about 10 and 6 % respectively. With a rise in the MMT percentage, the hardness exhibited a steady improvement. The tribological trials and ANOVA analysis demonstrated that the load has a greater effect on the friction coefficient than the sliding velocity. The specific wear rate and COF showed a decreasing trend up to the SR3 composition, but then rose for the SR4 composition. Also, when the load increased, the COF increased but the wear rate reduced. Both the coefficient of friction and the wear rate exhibit an upward trend, which increases the sliding velocity. The surface morphology of various configurations acquired by FE-SEM validates the mechanical and tribological experiment results. The SR3 composition

demonstrates a more uniform and uniformly distributed MMT. Adhesive wear is the predominant wear mechanism observed for the produced nanocomposite.

For the SR/MWCNT composite, tensile and tear strength are observed to rise with increasing filler loading, with composition SRC5 producing the best results. However, the SRC3 composition has the best tribological features. SR/Graphene nanocomposite exhibited excellent mechanical and tribological properties, making it suitable for a variety of automotive and other applications. 5 percent SR-graphene nanocomposite demonstrates the highest tensile and tear strength (SRG4). In comparison to the SRG1 composition, the tensile and tear strengths increased by more than 213 and 111 %, respectively. According to tribological experiments, the load has a bigger effect on the friction coefficient, whereas the sliding velocity has a greater effect on the wear rate. The specific wear rate and COF decrease till composition SRG3, then increase for compositions SRG4 and SRG5. In addition, as stress increases, COF increases while wear rate decreases. The coefficient of friction and the rate of wear rise as the sliding velocity increases. The surface morphology of diverse configurations recorded by FE-SEM provides support for the results of mechanical and tribological tests.

8. FUTURE SCOPE

We discovered some intriguing facts about EMI shielding material after doing a slew of different analyses. These can be tested in the near future. Following are some important observations:

- EMI SE stands to gain much from the study of CNT/graphene hybridization. In order to create a new EMI shielding material, it is possible to reduce the amount of filler required and take use of the altered aspect ratio.
- Millimeter wave bands have recently been introduced as a result of modern technologies. This research is necessary to determine whether the newly produced material is effective in shielding electromagnetic radiation in the specified frequency ranges.
- The use of 3-D printing technology in the EMI shielding material manufacturing process is another potential innovation. The ability to design extremely complex parts and products with 3-D printing is a huge benefit. For 3-D printing, the biggest challenge is producing filaments for the machine.

9. ORGANIZATION OF THESIS

CHAPTER 1 INTRODUCTION

The first chapter gives the introduction of the research. It builds a strong research case and lays a foundation for the research in the field of EMI shielding. Gives brief introduction about the EMI shielding. Enlists the important objective.

CHAPTER 2 LITERATURE SURVEY

This chapter gives the idea about the latest and profound literature with different materials used for EMI shielding. It also gives the understanding of EMI shielding theory. After studying the literature, a gap analysis is found.

CHAPTER 3 MATRIALS AND METHODS

Chapter three discusses the selection of material, manufacturing of the composite and characterization techniques used.

CHAPTER 4 CHARACTERIZATION OF MECHANICAL PROPERTIES

In chapter 4, profound results on mechanical characteristics of all the materials are discussed in detail.

CHAPTER 5 CHARACTERIZATION OF TRIBOLOGICAL PROPERTIES

In chapter 5 gives the detailed insight about tribological characterization results of all the materials.

CHAPTER 6 MODELING & SIMULATION OF SR MMT COMPOSITION

This chapter gives details about the theoretical background and the process of RVE modeling of nanocomposite.

CHAPTER 7 DIELECTRIC AND EMI SE STUDY

Chapter 7 gives the insightful discussion on the dielectric and EMI SE behavior of the manufactured nanocomposites. It also gives the details of simulation in Ansys Electronics using HFSS tool.

CHAPTER 8 CONCLUSION AND FUTURE SCOPE

Chapter 8 gives the profound conclusions and steeringdirections of the research work.

CHAPTER 9 REFERENCES

10. REFERENCES

[1] Grellier, J., Ravazzani, P., and Cardis, E., Potential Health Impacts of Residential Exposures to Extremely Low Frequency Magnetic Fields in Europe, *Environment International*, **62** (2014), 55–63.

[2] Kong, L. B., Li, Z. W., Liu, L., Huang, R., Abshinova, M., Yang, Z. H., Tang,

C. B., Tan, P. K., Deng, C. R., and Matitsine, S., Recent Progress in Some Composite Materials and Structures for Specific Electromagnetic Applications, *International Materials Reviews*, **58** (4) (2013), 203–259.

[3] Jeddi, J., Katbab, A. A., and Mehranvari, M., Investigation of Microstructure , Electrical Behavior , and EMI Shielding Effectiveness of Silicone Rubber / Carbon Black / Nanographite Hybrid Composites, (2019).

[4] Singh, A. K., Shishkin, A., Koppel, T., and Gupta, N., A Review of Porous Lightweight Composite Materials for Electromagnetic Interference Shielding, *Composites Part B: Engineering*, **149** (March) (2018), 188–197.

[5] Ganguly, S., Bhawal, P., Ravindren, R., and Das, N. C., Polymer Nanocomposites for Electromagnetic Interference Shielding: A Review, *Journal of Nanoscience and Nanotechnology*, **18** (11) (2018), 7641–7669.

[6] Han, R., Wang, Z., Zhang, Y., and Niu, K., Thermal Stability of CeO 2 /graphene/phenyl Silicone Rubber Composites, *Polymer Testing*, **75** (2019), 277–283.

[7] Dong, Y., Ke, Y., Zheng, Z., Yang, H., and Yao, X., Effect of Stress Relaxation on Sealing Performance of the Fabric Rubber Seal, *Composites Science and Technology*, **151** (2017), 291–301.

[8] Guan, Y., Yang, R., Huang, Y., Yu, C., Li, X., Wei, D., and Xu, X., Multi-Walled Carbon Nanotubes Acting as Antioxidant for Fluorosilicone Rubber, *Polymer Degradation and Stability*, **156** (2018), 161–169.

[9] Li, H., Tao, S., Huang, Y., Su, Z., and Zheng, J., The Improved Thermal Oxidative Stability of Silicone Rubber by Using Iron Oxide and Carbon Nanotubes as Thermal Resistant Additives, *Composites Science and Technology*, **76** (2013), 52–60.

[10] Dou, Z., Wu, G., Huang, X., Sun, D., and Jiang, L., Electromagnetic Shielding Effectiveness of Aluminum Alloy-Fly Ash Composites, *Composites Part A: Applied Science and Manufacturing*, **38** (1) (2007), 186–191.

[11] Wetherhold, R. C. and McManaman, J. M., EMI Shielding Effectiveness of Copper /epoxy Composites, *Polymers and Polymer Composites*, **13** (7) (2005), 657–668.

[12] Song, W. L., Cao, M. S., Lu, M. M., Bi, S., Wang, C. Y., Liu, J., Yuan, J., and Fan, L. Z., Flexible Graphene/polymer Composite Films in Sandwich Structures for Effective Electromagnetic Interference Shielding, *Carbon*, **66** (2014), 67–76.

[13] Dong, M., Li, Q., Liu, H., Liu, C., Wujcik, E. K., Shao, Q., Ding, T., Mai, X., Shen, C., and Guo, Z., Thermoplastic Polyurethane-Carbon Black Nanocomposite Coating: Fabrication and Solid Particle Erosion Resistance, *Polymer*, **158** (2018), 381–390.

[14] Luo, X. and Chung, D. D. L., Electromagnetic Interference Shielding Using Continuous Carbon-Fiber Carbon-Matrix and Polymer-Matrix Composites, *Composites Part B: Engineering*, **30** (3) (1999), 227–231.

[15] Antunes, M. and Velasco, J. I., Multifunctional Polymer Foams with Carbon Nanoparticles, *Progress in Polymer Science*, **39** (3) (2014), 486–509.

[16] Nanni, F., Travaglia, P., and Valentini, M., Effect of Carbon Nanofibres Dispersion on the Microwave Absorbing Properties of CNF/epoxy Composites, *Composites Science and Technology*, **69** (3–4) (2009), 485–490.

[17] Bahadur, S. and Sunkara, C., Effect of Transfer Film Structure, Composition and Bonding on the Tribological Behavior of Polyphenylene Sulfide Filled with Nano Particles of TiO2, ZnO, CuO and SiC, *Wear*, **258** (9) (2005), 1411–1421.

[18] Zhou, E., Xi, J., Guo, Y., Liu, Y., Xu, Z., Peng, L., Gao, W., Ying, J., Chen, Z., and Gao, C., Synergistic Effect of Graphene and Carbon Nanotube for High-Performance Electromagnetic Interference Shielding Films, *Carbon*, **133** (2018), 316–322.

[19] Ates, M., Eker, A. A., and Eker, B., Carbon Nanotube-Based Nanocomposites and Their Applications, *Journal of Adhesion Science and Technology*, **31** (18) (2017), 1977–1997.

[20] Zhang, W., Li, X., Shan, Z., Wang, S., and Xiao, Y., Surface Modification of Magnesium Hydroxide by Wet Process and Effect on the Thermal Stability of Silicone Rubber, *Applied Surface Science*, **465** (2019), 740–746.

[21] Wang, G., Liao, X., Yang, J., Tang, W., Zhang, Y., Jiang, Q., and Li, G., Frequency-Selective and Tunable Electromagnetic Shielding Effectiveness via the Sandwich Structure of Silicone Rubber/graphene Composite, *Composites Science and Technology*, **184** (October) (2019), 107847.

[22] Bhattacharyya, S., Sinturel, C., Bahloul, O., Saboungi, M. L., Thomas, S., and Salvetat, J. P., Improving Reinforcement of Natural Rubber by Networking of Activated Carbon Nanotubes, *Carbon*, **46** (7) (2008), 1037–1045.

[23] Penkov, O., Kim, H. J., Kim, H. J., and Kim, D. E., Tribology of Graphene: A Review, *International Journal of Precision Engineering and Manufacturing*, **15** (3) (2014), 577–585.

[24] Sang, G., Dong, J., He, X., Jiang, J., Li, J., Xu, P., and Ding, Y., Electromagnetic Interference Shielding Performance of Polyurethane Composites: A Comparative Study of GNs-IL/Fe 3 O 4 and MWCNTs-IL/Fe 3 O 4 Hybrid Fillers, *Composites Part B: Engineering*, **164** (January) (2019), 467–475.

11. LIST OF PUBLICATIONS

[1] Avinash, S., Irulappasamy, S., Selvan, C. P., Sultan, M. T. H., Hua, L. S., and Munde, Y., Abrasive Machining Characteristics and Prediction Model for Sisal/Polyester Sandwich Composite, Journal of Natural Fibers, **0** (0) (2021), 1–17.

[2] Shinde, A., Siva, I., and Munde, Y., Micromechanical Simulation of Silicon Rubber Reinforced with MMT Nanoclay, Materials Today: Proceedings, (2022).

[3] Shinde, A., Siva, I., Munde, Y., Deore, V., Hameed Sultan, M. T., Md Shah, A. U., and Mustapha, F., Testing of Silicon Rubber/Montmorillonite Nanocomposite for Mechanical and Tribological Performance, Nanomaterials, **11** (11) (2021), 3050.